Addressing the requirements for RF photonics

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ABSTRACT

This paper address the relationship between system requirements and device specifications and figures of merit for RF photonic applications.

1. INTRODUCTION

Photonics has many attributes that makes it attractive for space-based platforms[1]. These include the size, weight, low loss, flexibility, and EMI resistance of the optical fiber as well as the wideband capability of photonics. Some of the potential applications of microwave photonics in space-based platforms include RF distribution links, antenna remoting, and true time delay. There remains however many challenges with respect to size weight, and power (SWaP) as well as the RF performance requirements. The challenge to meeting these system requirements is, in the end, a challenge to improving the individual components.

The starting point for discussing the insertion of photonics in space-based platforms is the point to point fiber optic link shown in Fig. 1. Here we show an externally modulated, direct detection link. To the basic link, various processing functions can be added, such as time delay, switching, or receiver pre-processing. From the RF perspective, the performance impact of the photonic link appears very much like that of an amplifier, being characterized, in addition to frequency and bandwidth, by its gain (G), noise figure (NF), third order intercept point (IP3), as well as its power consumption. However, the photonic link is not developed as a complete subsystem, but rather the individual components are developed separately. In this paper we address the figures of merit which are used with these components, and in particular, the optical modulator.

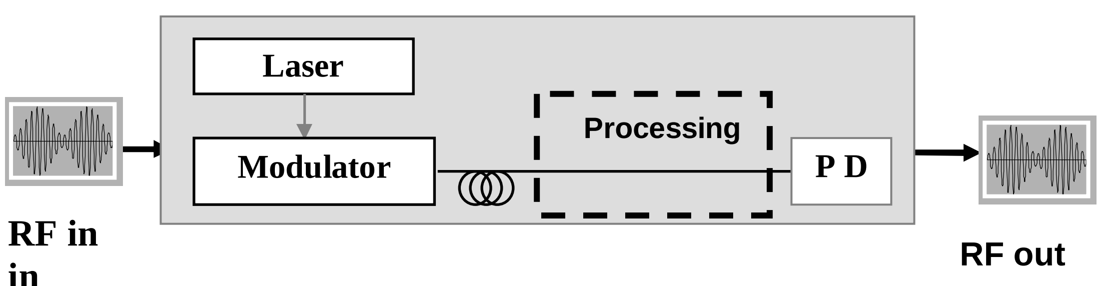

Figure 1 Photonic Link.

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14. ABSTRACT

This paper addresses the relationship between system requirements and device specifications and figures of merit for RF Photonic applications. This paper has focused on the optical modulator, as it is the key component in achieving the required RF performance within the constraints of space-based platforms. The modulator transfer function can be used to express the key parameters of the modulator, which are then used characterize the photonic link performance; G, NF, and IP3. Modulation efficiency S is preferred over $V\pi$ because it accounts for the insertion loss. The input IP3 can also be calculated directly from the transfer function.

15. SUBJECT TERMS

RF Photonics, optical modulator space-based platforms, photonic link

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2. Modulation Efficiency.

Modulation efficiency is important to any photonic link, but it is particularly important to space-based platforms where total power is limited. It is a characteristic of the modulator. V_π has been commonly used as figure of merit for external modulators, and has often been associated with modulation efficiency. Indeed, there has been a significant effort in recent years to reduce modulator V_π. However, as we discuss below, V_π is not the same as modulation efficiency.

In this section we define the modulation efficiency and V_π figures of merit for the external modulator. These are based the relationship of the transfer function to the RF gain. We define P_{in} to be the optical power in the fiber which is input to the modulator, and P_{out} to be the optical power coupled out of the modulator into the fiber. The optical power on the photodetector P_D, is $P_D = \eta_F P_{out}$, where η_F is the optical loss in the fiber. We assume that P_{out} is defined by the transfer function $T(V)$, such that $P_{out} = P_{in}T(V)$, where V is the applied voltage. Here the transfer function T includes the input and output coupling losses as well as the modulator absorptive and bias losses. The DC current in the photo detector is $I_D = \eta_D P_D$, where η_D is the photodetector responsivity. The RF power depends upon the ac part of the photodetector current, which is given by

$$I_{ac} = [P_{in} T'(V_b)\eta_D \eta_F]V_{RF}\,, \tag{1}$$

where

$$T'(V_b) = \left.\frac{dT}{dV}\right|_{V=V_b} \tag{2}$$

is the slope of the transfer function at the bias voltage V_b, and V_{RF} is the ac voltage applied to the modulator. The RF gain, G, defined as the ratio of the RF power out of the modulator to the RF power into the modulator, can then be expressed as

$$G = [P_{in} T'\eta_D \eta_F]^2 R_D R_M\,. \tag{3}$$

where, R_D and R_M are the photodetector and modulator resistances. We define modulation efficiency S to be equal to the slope of the transfer curve

$$S = T'\,. \tag{4}$$

Then, the RF gain is proportional to the square of the modulation efficiency.

V_π is a commonly used figure of merit for external modulators. For a Mach-Zehnder Modulator (MZM) the meaning of V_π is well defined. It is the voltage which produces a

π phase change between the two arms of the Mach-Zehnder interferometer. It is also the voltage that produces a maximum change in the output. The MZM has a transfer function, given by

$$T_{MZM}(V) = \eta_M \frac{1}{2}[1 + \cos(\frac{\pi V}{V_\pi} + \varphi)], \tag{5}$$

where η_M is the modulator losses (coupling and absorptive) and φ is a phase angle. For a MZM biased at quadrature the RF gain of a photonic link can be expressed in terms of the photodector current $I_{D,}$

$$G = \left[\frac{I_D \pi}{V_\pi}\right]^2 R_D R_M \,, \tag{6}$$

Alternately, the RF gain can also be expressed in terms of the optical input power:

$$G = \left[\frac{P_{in} \eta_m \eta_D \eta_F \pi}{2V_\pi}\right]^2 R_D R_M \,. \tag{7}$$

The V_π figure of merit is specific to Mach-Zehnder modulators. However, for other types of external modulator, such as electro-absorption modulators (EAM) and directional coupler modulators (DCM) it has been convenient to define an equivalent V_π such that the expression for RF gain is the same as that of the MZM. This has led to two somewhat different definitions for V_π equivalent, depending on which expression for the RF gain is used. This V_π equivalent can be expressed in terms of the transfer function.

If equation (6) is used to express the RF gain, then V_π equivalent is defined as[2]

$$V^*_{\pi eq} = \pi \frac{T(V)}{T(V)'} \tag{8}$$

If equation (7) is used to express the RF gain, then V_π equivalent is defined as

$$V_{\pi eq} = \frac{\pi}{2} \frac{1}{T_N'} \tag{9}$$

where T_N is the normalized transfer function, given by

$$T_N = \frac{T(V)}{\eta_m} \,. \tag{10}$$

Then the gain can be expressed as

$$G = \left[\frac{I_D \pi}{V^*_{\pi eq}} \right]^2 R_D R_M \tag{11}$$

or

$$G = \left[\frac{P_{in} \eta_m \eta_D \eta_F \pi}{2V_{\pi eq}} \right]^2 R_D R_M \tag{12}$$

It should be emphasized that $V^*_{\pi eq}$ and $V_{\pi eq}$ are not interchangeable in equations (11) and (12). $V^*_{\pi eq}$ and $V_{\pi eq}$ both use a normalized transfer function, but the normalization is defined in different ways. $V^*_{\pi eq}$ is normalized with respect to the transmission at the bias voltage, while $V_{\pi eq}$ is normalized with respect to the transmission at 0 bias.

The main issue addressed here is identification of the appropriate figure of merit to use for space based applications. V_π has traditionally been used as the primary figure of merit for external modulators. For all other parameters remaining the same, a reduction in V_π does correspond to improved modulator efficiency. However, V_π is not the same as modulation efficiency. This is because V_π is defined with respect to a normalized transfer function, and is therefore independent on the insertion loss of the modulator.

For some analog applications power consumption is not a concern, and insertion loss can be overcome with increased optical power. For some high frequency applications drive voltage is a primary concern. For these applications V_π may be the more relevant figure of merit for the modulator. For space-based applications power consumption is quite important, and the power budget allowed for the photonic link is generally limited. For such applications it is more desirable to have a single figure of merit for modulation efficiency that contains both V_π and the insertion loss (η_m). The modulation efficiency S defined by equation (4) does just that. As seen by equation (3), it is the slope of the transfer function that expresses the modulator's effect on gain. These points are illustrated in Figs. 2 - 4. The solid curves T_1 and T_2 in Fig 2. correspond to two different transfer curves which have the same normalized transfer curve T_N, but different insertion loss. These are cosine transfer curves of a MZM with a $V_\pi = 1$. Both would be characterized with the same value of V_π, but the slope is reduced by the insertion loss, as indicated in Figure 3. In fact, it is the insertion loss that reduces the modulation efficiency, while the bias loss does not. Figure 4 shows the corresponding values of $V^*_{\pi eq}$ and $V_{\pi eq}$ as a function of bias voltage. $V^*_{\pi eq}$ and $V_{\pi eq}$ are both equal to $V_\pi = 1$ at V = 0.5, which corresponds to the quadrature bias point, as the definitions for these FOMs are defined relative to the MZM biased at quadrature. However, the functional form is quite different. $V^*_{\pi eq}$ goes to zero at the low bias point. However, the transmission and modulation efficiency (slope) also go to zero at the low bias. It would take an infinite amount of optical power to obtain the constant current I_D imposed by equation (11).

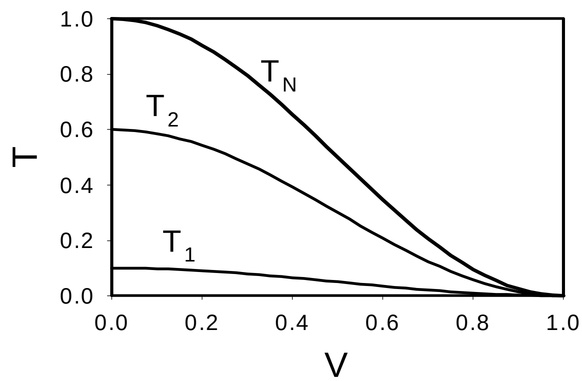

Fig 2. Transfer curves T_1 and T_2, and normalized transfer curve T_N.

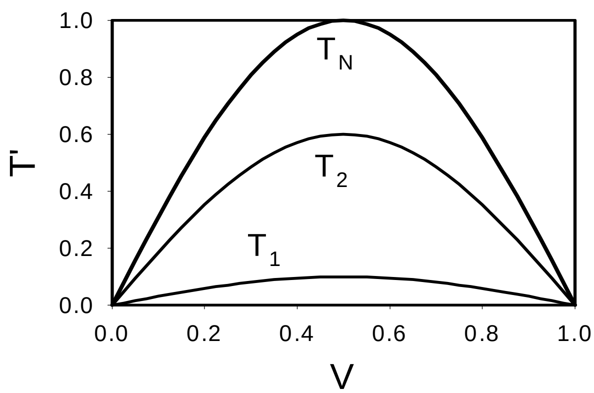

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Fig. 3. Slopes of the transfer curves shown in Fig. 2.

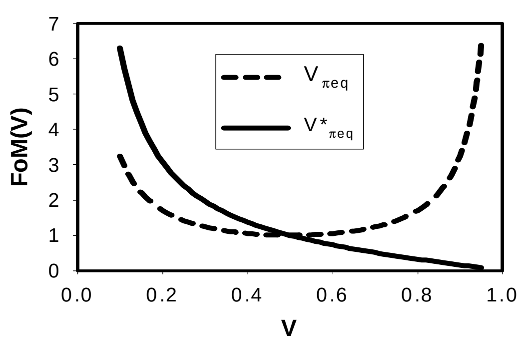

Fig 4. Figures of merit for the normalized transfer curve T_N.

As illustrative examples consider the modulation efficiency of a $LiNbO_3$ MZM with a 4V V_π and insertion loss of 3 dB (S = 0.2). The polymer MZM reported by Shi *et al.*[3] had a V_π *=0.8*, but an insertion loss of over 13 dB, with a corresponding modulation efficiency of *S=0.1*. Similarly, the EAM modulator reported by Welstad *et. al*[4] had $V_{\pi eq}$*=1.1V*, but with an insertion loss of over 27 dB the modulation efficiency was only *S=0.028.*

3. Noise Figure

Noise figure is often more important of a concern for the system impact of the photonic link than the gain. While low gain can be compensated with post amplifiers, high link NF can put severe requirements on a low noise pre amplifier. Noise figure is defined in terms of the ratio of the SNR_{in} to the SNR_{out}, and for the photonic link can be expressed as[5]

$$NF = 10\log(2 + \frac{1}{G} + \frac{N_S + N_{RIN}}{kT_B G}) \qquad (13)$$

where N_S is the Shot noise which is proportional to I_D, and N_{RIN} is the RIN noise which is proportional to I_D^2, k is Boltzmann's constant, and T_B is the temperature. Noise figure is reduced with increasing gain. With respect to the modulator, modulation efficiency is the appropriate figure of merit for NF, in the same way that it is for gain. In Figure 5 we plot NF as a function of modulation efficiency, for a photodetector current of 4 mA and a RIN of -170 dB/Hz. For these parameters a modulation efficiency of 10 V^{-1} corresponds to a gain of about 12 dB There are families of curves that depend on laser power and RIN.

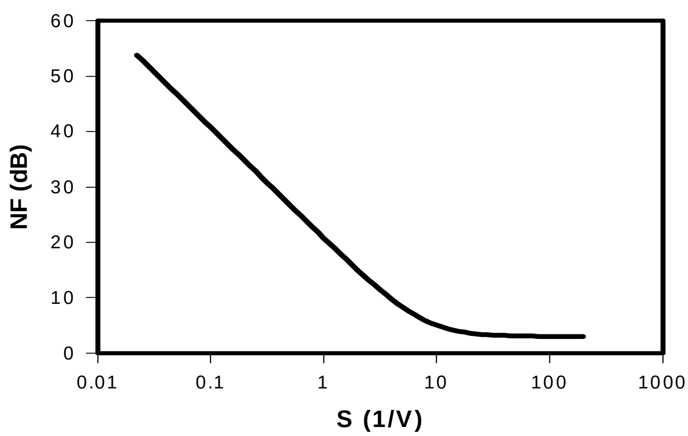

Figure 5. Noise Figure vs modulation efficiency.

4. SFDR / IP3

The linearity of a photonic link is often defined in terms of the two-tone SFDR for which the third order intermodulation term is the dominant spur. This is the case for sub-octave bandwidths. The SFDR is equal to the SNR at the input power at which the intermodulation spur is equal to the noise. The SFDR then can be expressed as[3]

$$SFDR = [IP3 + 174 - NF - 10\log(BW)]\,{}^{2}\!/_{3}, \qquad (14)$$

where *IP3* is the input IP3 RF power in dBm and BW is the bandwidth. Here it is of course assumed that the intermodulation term has a third order dependence on the input power.

In cascading RF components it is the IP3, G, and NF that are used in determining the over all system characteristics. The issue addressed here is the definition an appropriate figure of merit for a modulator that expresses the linearity. We start with of a two-tone input :

$$V(t) = V_b + V_0[\sin(\omega_1 t) + \sin(\omega_2 t)] \qquad (15)$$

We expand the transfer function in a Taylor series about the bias voltage V_b:

$$T(V) = T(V_b) + \sum_{n=1}^{\infty} \frac{1}{n!}\left(T^n\right)\left(V - V_b\right)^n \qquad (16)$$

where

$$T^n = \left(\frac{d^n T}{dV^n}\right)_{V=V_b} \qquad (17)$$

We keep terms to 5th order. Then the power out at the fundamental is given by

$$T_1(V) = T^1 V_o + \frac{3}{8} T^3 V_o^3 + \frac{5}{96} T^5 V_o^5 \qquad (18)$$

For suboctave operation, the dominate spurious signal is usually due to the intermodulation term at $2\omega_1$-ω_2, or $2\omega_2$-ω_1. This can be expressed as

$$T_{IM}(V) = \frac{1}{8}T^3V_o^3 + \frac{5}{192}T^5V_o^5 \qquad (19)$$

If the intermodulation term is dominated by the third order term, then it is meaningful to define the input IP3 point, determined by keeping only the first terms in equations 18 and 19, setting $T_1 = T_{IM}$, and solving for V_o. Then V_{IP3} is given by

$$V_{IP3} = \sqrt{8\frac{T^1}{T^3}} \qquad (20)$$

*IP3*can then be determined from V_{IP3}. This is attractive as a modulator parameter because the *IP3* point of the photonic link depends only on the modulator (T and R_M) and is used to determine the SFDR. This assumes that the photo-diode is operated at an optical power sufficiently below saturation such that it does not limit the SFDR.

It follows from equation (5) that for an MZM

$$V_{IP3} = \sqrt{8}\frac{\pi}{V_\pi}. \qquad (21)$$

Thus, reducing V_π may increase the gain and lower the *NF*, but it can compromise the SFDR. This is seen in Figure 6, where we plot the *SFDR* for a MZM as a function of V_π,

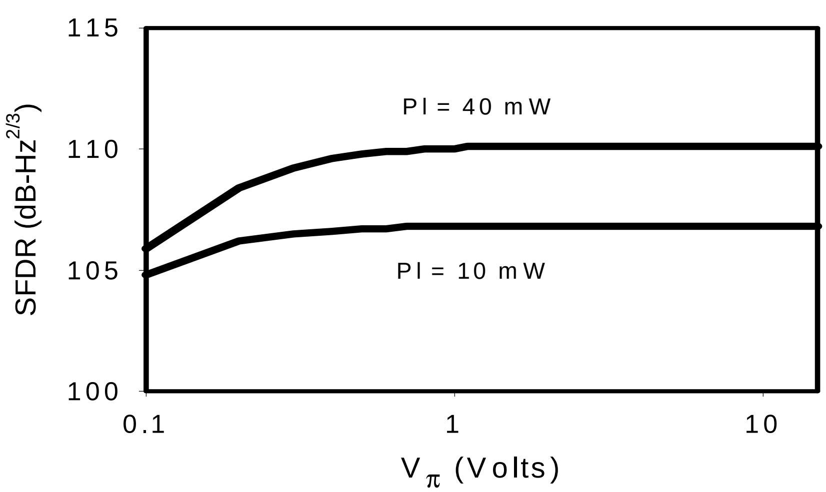

Figure 6. SFDR of a MZM as a function of V_π .

for two different laser powers. Here we have assumed 3dB insertion loss and laser RIN is -170 dB/Hz. This behavior in the SFDR can be seen by examination of equation (14). As V_π decreases the input *IP3* also decreases according to equation (21). From equation (13) and Figure 5, the noise figure also decreases with increasing gain associated with decreasing V_π (increasing modulation efficiency). Thus, with decreasing V_π, *NF* saturates while the input *IP3* continues to decrease, resulting in a reduced *SFDR*.

Analysis of equation (20) suggests that the appropriate strategy for increasing *IP3*, and therefore the SFDR, would be to minimize the third order derivative of the transfer function. This is indeed the strategy employed for many so called "linearized modulators". However, this approach is usually limited because the fifth order term in equation (19) then dominates.

5. SUMMARY

This paper has focused on the optical modulator, as it is the key component in achieving the required RF performance within the constraints of space-based platforms. The modulator transfer function can be used to express the key parameters of the modulator, which are then used characterize the photonic link performance; G, NF, and IP3. Modulation efficiency *S* is preferred over V_π because it accounts for the insertion loss. The input *IP3* can also be calculated directly form the transfer function.

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